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TECHNICAL NOTE 4097

INVESTIGATION OF SOME MECHANICAL PROPERTIES

OF THERMENOL COMPRESSOR BLADES

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OF THERMENOL COMPRESSOR BLADES

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SUMMARY

A series of tests were made comparing the mechanical properties of similar compressor blades of AISI type 403 stainless steel and thermenol. Eighth-stage J47 and J65 compressor blades of each material were tested.

Comparison in bending and torsional deflection tests showed thermenol to have a modulus of elasticity of about 26×10^6 and a modulus of rigidity of about 9×10^6.

The thermenol blades had a logarithmic decrement of damping of 3.35 percent compared with 4.9 percent for stainless steel. The damping measurements were made using the resonant peak method at stresses close to the fatigue limit of the materials.

The thermenol blades showed no surface corrosion due to exposure to a salt spray for about 30 hours, whereas the stainless-steel blades were badly rusted and pitted. The thermenol blades exhibited fatigue strength equal to or higher than the stainless-steel blades both before and after being subjected to a salt spray.

INTRODUCTION

In the search for greater efficiency and reliability in jet-engine compressors, new materials are being sought constantly. Stainless-steel blades are in common use because of their desirable damping, corrosion-resistance, and fatigue-strength properties. Where exciting forces and, hence, vibratory stresses are low and the temperature is moderate as in the middle stages of the compressor, aluminum and aluminum-bronze blades have been used to advantage because of their light weight. Titanium has desirable qualities, particularly light weight, but it has been used only to a limited extent, because of its high cost. High damping and low weight are also available in blades made of fiberglass impregnated with plastic resins.

There are several essential properties that a compressor blade must possess such as high fatigue strength, high damping, high impact strength, resistance to corrosion, low density, ease of fabrication, and availability. Blades are subjected to vibratory forces through most of the speed range of the engine. To withstand these forces the blades must have a combination of sufficient fatigue strength and damping. If the material damping is high, the vibratory stresses are kept low and a lower fatigue strength will suffice. Blades must be resistant to corrosion because of the huge quantities of air that pass through the engine and impinge on the blades. Of particular interest in this respect are naval aircraft used in regions where salt spray is prevalent. The importance of low density, ease of fabrication, and availability is self-evident. Some degree of impact strength is necessary because of the ever-present danger of foreign objects entering the compressor. Blades must be capable of sustaining damage in the form of nicks and dents without failing.

In the past 3 years a considerable amount of interest has been shown in the thermenol alloys. Thermenol is the name assigned by the U.S. Naval Ordnance Laboratory to iron-base alloys containing nominally 10 to 18 percent aluminum and 2 to 4 percent molybdenum. It was originally developed for use in transformer cores because of its desirable permeability properties and good high-temperature corrosion resistance. Because of its corrosion resistance, low density, and some other desirable features, it has been considered as a compressor-blade material. Considerable data are available on the strength properties of thermenol (refs. 1 and 2). However, all these data were obtained using laboratory specimens. Experience has shown that when an alloy is formed into a working shape its strength characteristics can change considerably. This can be due to many effects such as geometry and working. Therefore, the tests made in this investigation used conventional compressor rotor blades. It is the purpose of this investigation to compare mechanical properties of compressor blades made of AISI type 403 stainless steel, which is one of the most common compressor-blade materials, with those of thermenol. This study compares damping, fatigue, fatigue after being subjected to salt spray, bending and torsional deflection, and tensile strength.

SYMBOLS

d   deflection

E   modulus of elasticity

F(k)   function of polar moment of inertia

f(I)   function of moment of inertia

f_p frequency at peak amplitude

G   modulus of rigidity

l length

n   width of resonant curve in cycles at $0.707 \times$ peak amplitude

P   load

Q   torque

δ   logarithmic decrement

θ   angle of twist

Subscripts:

s   steel

t   thermenol

APPARATUS AND PROCEDURE

Two types of compressor rotor blades supplied by the U.S. Navy were used, J65 and J47, and both types were from the eighth stage. In order to determine the suitability of the thermenol blades they were compared in all tests with standard-production AISI type 403 stainless-steel blades.

Bending Deflection

The tip of the test blade was deflected by means of a push rod loaded with weights. A steel ball formed the bearing point between the rod and blade. The blade was deflected so as to impose compression on the concave side of the blade. Weights from 0 to 30 pounds at 1-pound increments were used, and the deflection was measured using a dial indicator. In addition, the stress at the point of maximum thickness on the convex side at the base of the blade was measured with a resistance-wire strain gage.

The formula for the deflection at the tip of a cantilever blade of arbitrary distribution of moment of inertia along the span and with a concentrated load at the tip is

$$d = \frac{Pl^3}{3E} \ f(I)$$

where $f(I)$ is a function depending on the distribution of moment of inertia along the span. Comparing the deflections obtained for the steel blades with those from the thermenol blades and assuming the moment of inertia distributions to be the same gave the following expression for the modulus of elasticity of the thermenol blade in terms of the known modulus of elasticity of steel:

$$E_t = \frac{d_s}{d_t} E_s$$

The value obtained from the literature for the modulus of elasticity of 403 stainless steel was 28×10^6 psi.

Torsional Deflection

The tip of the blade was fitted with a clamp that was formed to fit the cross section of the blade at the tip and that was supported at the approximate center of torsion by a ball bearing to prevent the blade from bending (fig. 1). A torsional lever arm and a pointer were attached to the clamp. Several torques ranging from 0 to 4.5 foot-pounds were applied by hanging weights on the lever arm. Angular deflections were obtained using the pointer and a fixed scale.

The formula for the angle of twist of a cantilever blade due to a moment at the tip is

$$\theta = \frac{Q l}{G} F(k)$$

where $F(k)$ is a function of the polar moment of inertia. Comparing the angular deflections obtained from the steel blades with those from the thermenol blades and assuming the functions of polar moment of inertia to be the same yielded the following expression for the modulus of rigidity of the thermenol blade in terms of the known modulus of rigidity of steel:

$$G_t = G_s \frac{\theta_s}{\theta_t}$$

The value from the literature used for the modulus of rigidity of the steel blade was $G = 10 \times 10^6$ psi.

Damping

In order to obtain damping values at stresses close to the fatigue limit, the resonant peak method was used. In this method, advantage is taken of the fact that the width of the resonant peak is proportional to the damping. Logarithmic decrement varies directly with the frequency

range of the resonant curve at 0.707 × peak amplitude divided by the frequency at peak amplitude. The blade was excited in its fundamental bending mode using an air interrupter. The air interrupter consisted of a disk with 18 equally spaced holes about its periphery. The disk was rotated by an electric motor with electronically controlled speed. A high-pressure air jet was arranged to impinge on the tip of the blade perpendicular to the blade face after passing through the peripheral holes in the disk. Resonance curves were obtained at peak stresses ranging from about ±20,000 psi up to the fatigue limit of each material. Stresses were measured with resistance-wire strain gages, and vibratory frequency was measured with an electronic counter.

The formula for logarithmic decrement is

$$\delta = \frac{\pi n}{f_p}$$

Fatigue

The blades were excited into vibration with a high-pressure air jet. The jet nozzle was aimed at the tip end of the blade parallel to the longitudinal blade axis. Since only a limited number of blades were available, each blade was started at a safe stress level. When 10^8 cycles were completed, the stress was raised 3,000 to 5,000 psi by increasing the air pressure and the fatigue test was repeated. In this way the endurance limit was approximately established. A few blades were tested at single stresses above the endurance limit in order to establish the S-N curve.

Salt-Water Corrosion

One J65 blade of each material and two J47 blades of each material were subjected to a salt-water mist before being tested in fatigue. Two small atomizer jets were arranged to spray the blade from both sides at approximately midspan. In order to simulate sea-water conditions, sea salt, as used in marine aquariums, was added to the water until the specific gravity was 1.02 to 1.03. The whole unit was confined in a glass tank in order that the water could be collected and reused. Each blade was run approximately 24 to 32 hours in the spray tank.

Tensile Strength

One flat tensile specimen was cut from each of two J65 thermenol blades. Even though extreme care was taken when grinding the specimens, many surface cracks could be observed in a zyglo test (fig. 2). The

specimens were pulled in a conventional tensile machine, and strains were
measured with resistance-wire strain gages. The ends were gripped in
such a way that bending of the specimen was kept to a minimum.

RESULTS AND DISCUSSION

The flexural strength of a thermenol blade is compared with the
flexural strength of a steel blade in figure 3. The modulus of elastic-
ity of the thermenol blades was calculated on the basis of these data to
be about $E_t = 26 \times 10^6$ psi.

The torsional stiffness of thermenol blades is compared with that
of steel blades in figure 4, and the modulus of rigidity was calculated
on the basis of this comparison to be about $G_t = 9.0 \times 10^6$ for the ther-
menol blades.

Figure 5 shows that at all stresses from 20,000 to 60,000 psi the
AISI type 403 stainless-steel blades have higher damping than the ther-
menol blades. At 56,500 psi the steel blades had 4.9 percent damping
compared with 3.35 percent damping of the thermenol blades.

An S-N diagram is presented in figure 6. Many more specimens would
have to be tested in fatigue in order to present an accurate group of
curves because of the spread inherent in fatigue data. However, some
definite conclusions can be drawn from figure 6. Of the two groups of
thermenol blades, the J47 blades were definitely superior. Metallo-
graphic examinations made on specimens from almost all the blades showed
three distinct reasons for this superiority:

(1) The J47 blades exhibited elongated grains indicating more cold
     work.

(2) The J47 blades exhibited smaller grain size.

(3) There was evidence of slightly more precipitation.

The J47 thermenol blades showed equal fatigue strength (82,000 psi)
when compared with the J47 steel blades. The J65 thermenol blades showed
a fatigue strength of 58,000 psi. The J65 steel blades were not included
because they were of inferior quality; there were chordwise tool marks
at the base of the blades due to finishing, and they failed without ex-
ception at the location of the tool marks at low stresses.

It is possible to manufacture 403 stainless-steel blades with fa-
tigue limits higher than 58,000 to 60,000 psi. With proper heat-treating
methods, fatigue limits on the order of 90,000 psi can be realized. It
can be assumed that the fatigue limit of thermenol might likewise be

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improved as evidenced by the difference between the J47 and J65 thermenol blades. However, the damping might be lowered, which would not necesarily be desirable.

After being subjected to a salt spray for 24 to 32 hours there was no corrosion evident on the surface of the thermenol blades, whereas the 403 stainless-steel blades had large rust spots on them. Figure 6 shows that the thermenol blades lost less strength than the steel blades.

The tensile tests showed that the ultimate strength of one specimen was 77,000 psi and of another 91,000 psi. These tensile data are probably low indications of the material potential, since if the many surface cracks were eliminated the ultimate tensile strength should rise. Extreme care must be taken when cutting or grinding thermenol. Many shallow cuts must be made to avoid the cracks shown in figure 1. However, several specimens have been ground since for another series of tests and no cracks were evident. Therefore, the material can be worked if proper precautions are taken.

SUMMARY OF RESULTS

	Thermenol	AISI type 403 stainless steel
Modulus of elasticity	26×10^6	28×10^6
Modulus of rigidity	9×10^6	10×10^6
Damping - logarithmic decrement (56,500 psi)	3.35 Percent	4.9 Percent
Fatigue limit J65	58,000	
Fatigue limit J47	82,000	82,000
Corrosion of surface by salt spray	None	Rust
Fatigue strength of sprayed blades (average of two J47 blades)	Thermenol superior to steel	
Tensile strength (ultimate) for two specimens	77,000 and 91,000 psi	

Thermenol is in most respects equal to AISI type 403 stainless steel as a compressor-blade material and in a few respects it is superior, but it is inferior in damping capacity. The lower density and superior corrosion resistance make it a very desirable material for possible use in compressor blades.

Lewis Flight Propulsion Laboratory
        National Advisory Committee for Aeronautics
                Cleveland, Ohio, August 9, 1957

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1. Nachman, J. F., and Buehler, W. J.: Applications, Properties, and Fabrication of Thermenol Type Alloys. NAVORD Rep. 4237, U.S. Naval Ord. Lab., May 4, 1956.

2. Gyorgak, Charles A.: Preliminary Investigation of Stress-Rupture and Tensile Strength of Thermenol, an Iron-Aluminum Alloy. NACA RM E54F10, 1954.
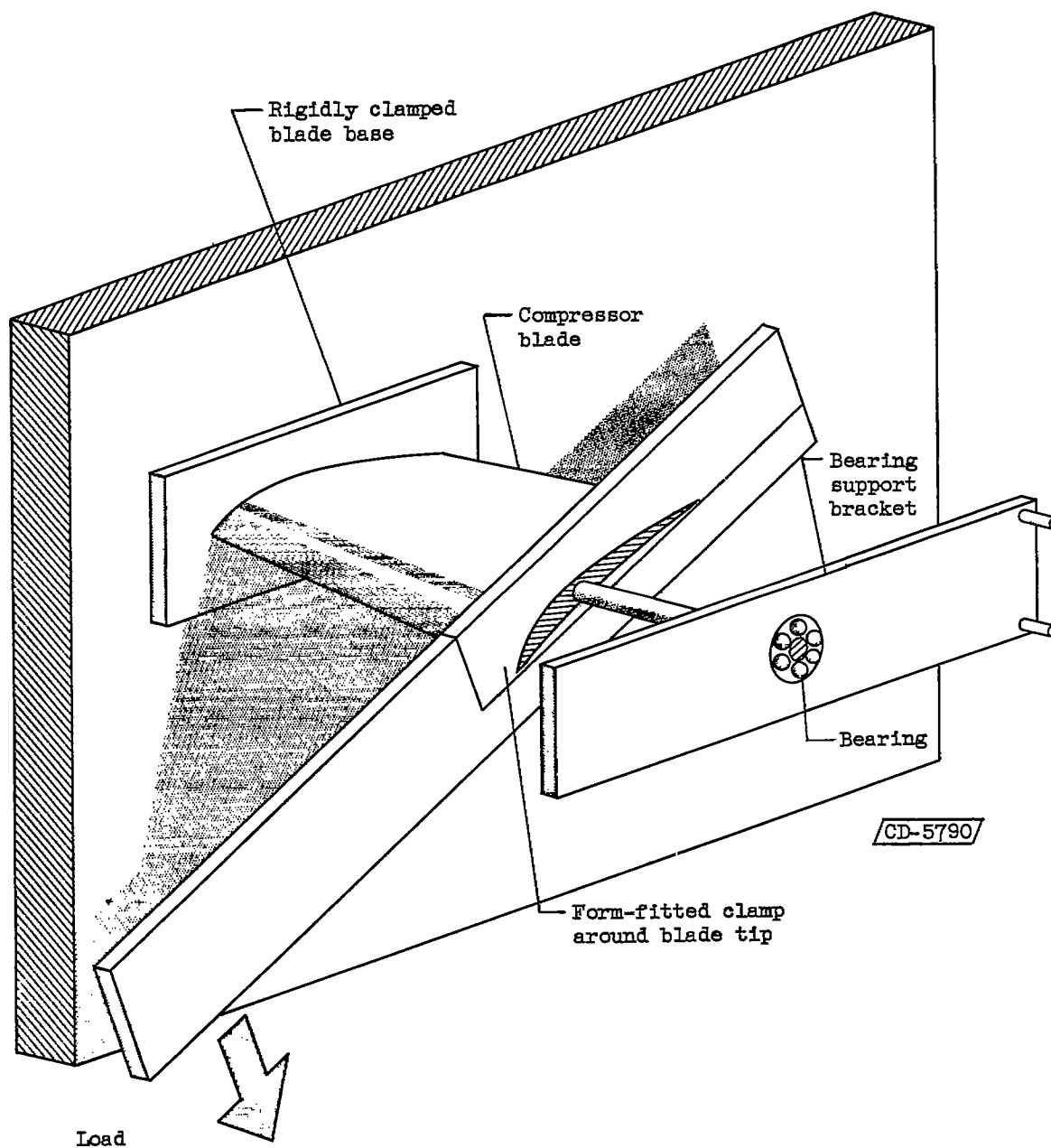
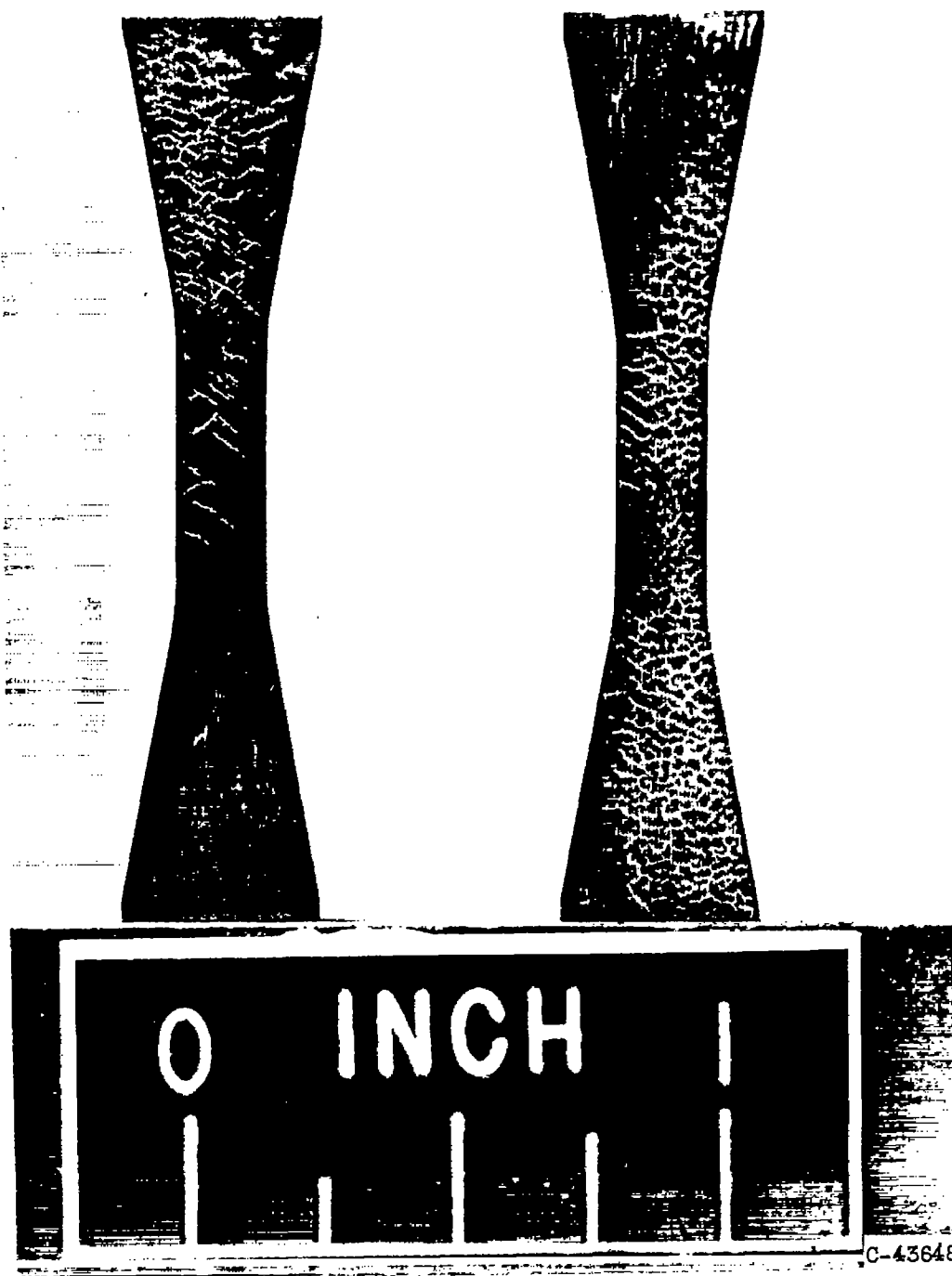Figure 1. - Partially exploded schematic drawing of torsion test apparatus.

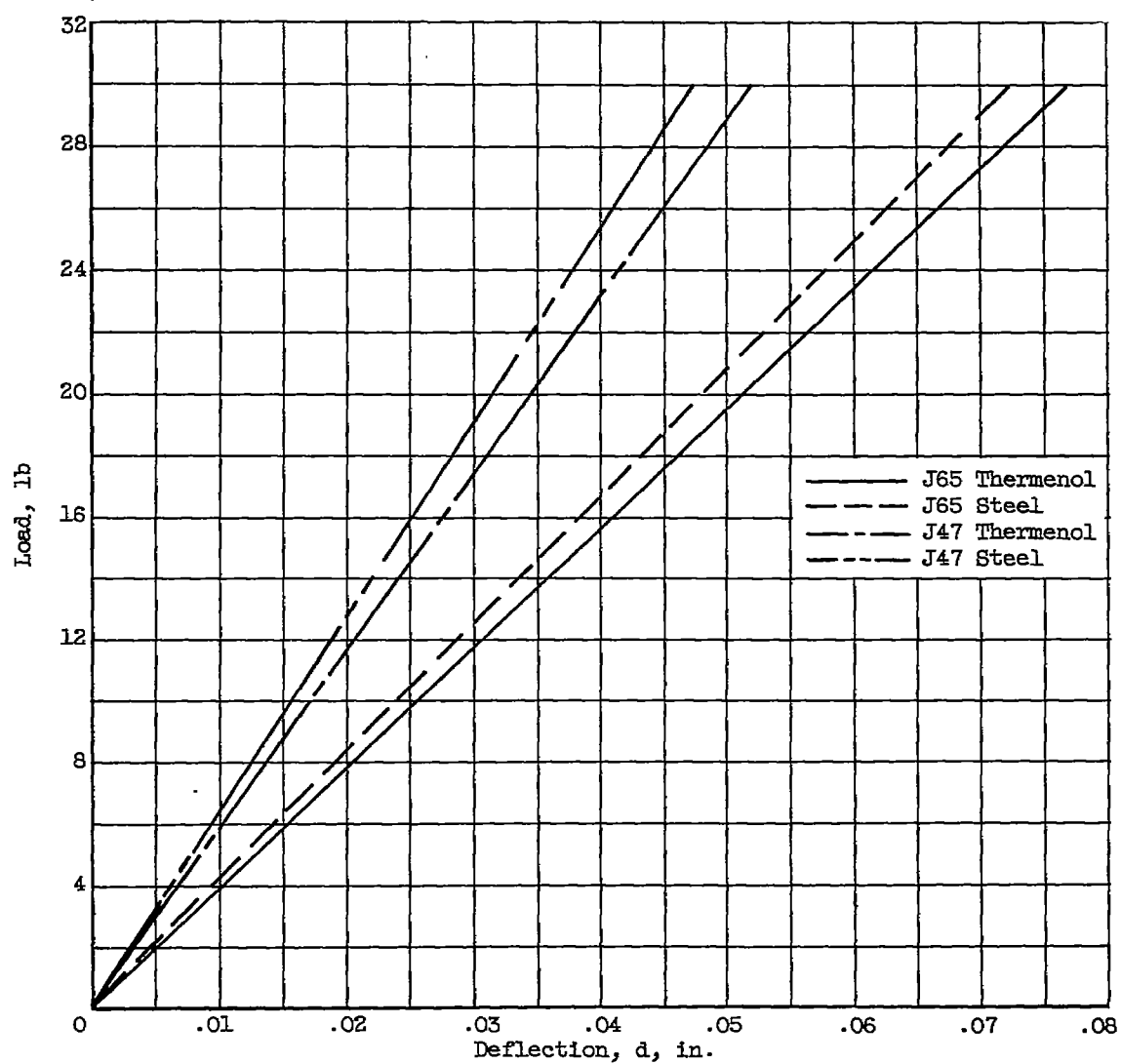Figure 2. - Zyglo indications of surface cracks of thermenol tensile specimens.

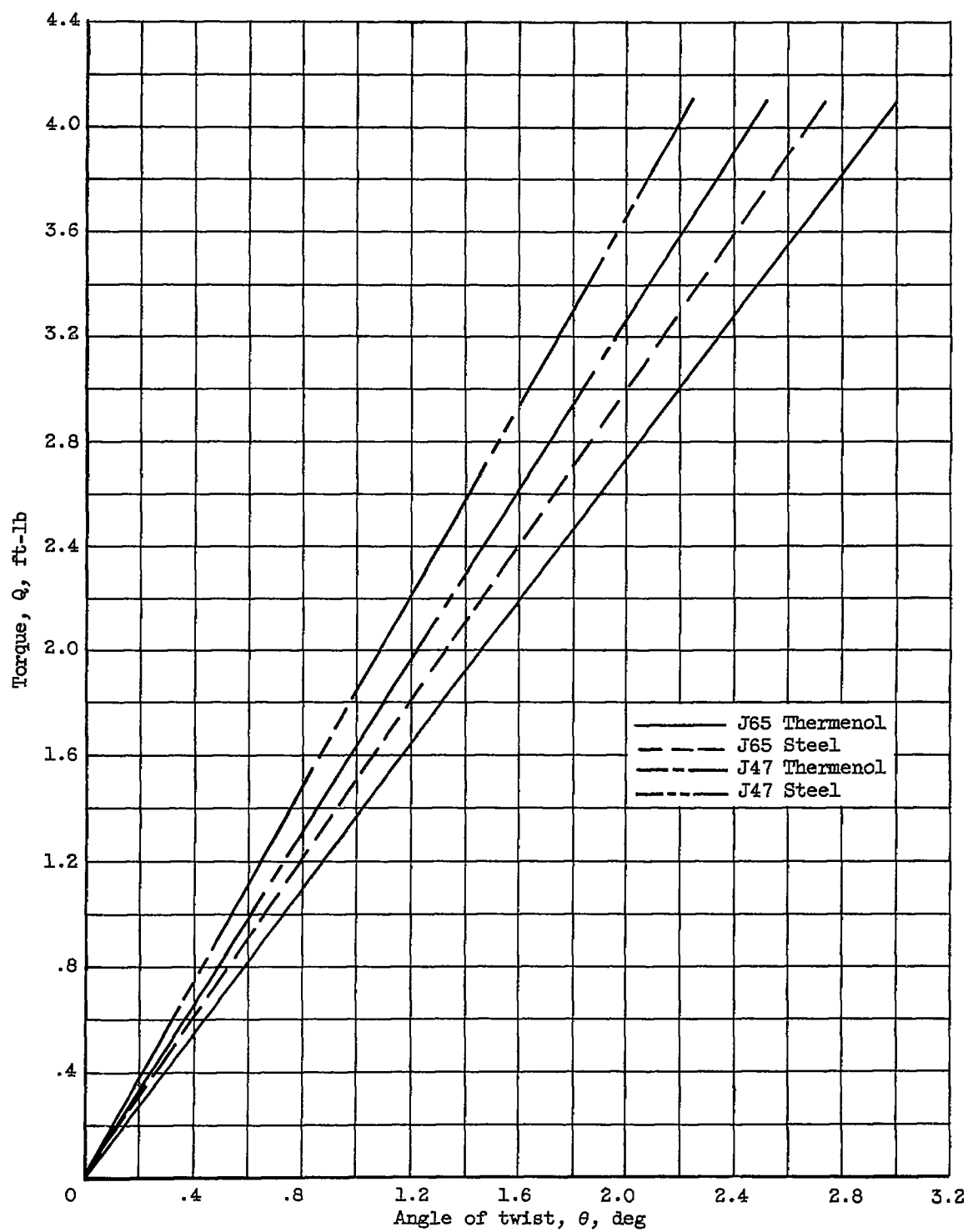Figure 3. – Average deflections of steel and thermenol blades.

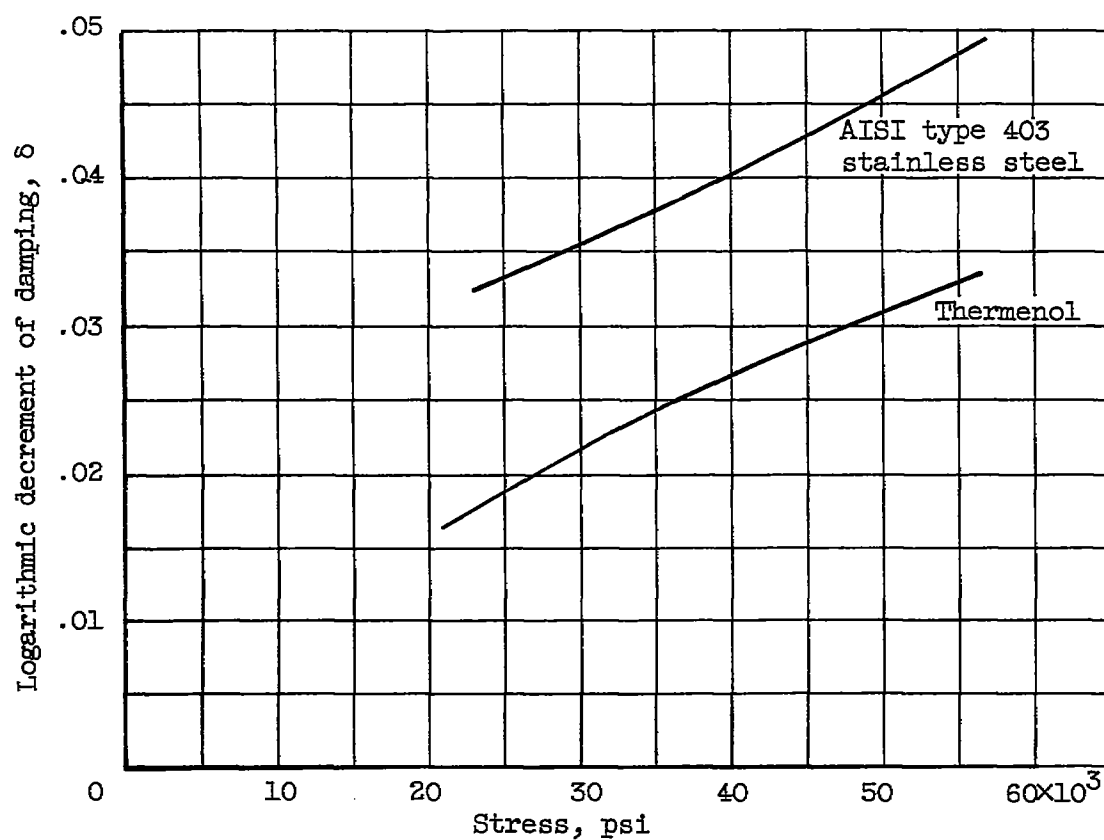Figure 4. - Average twist of steel and thermenol blades.

Figure 5. - Comparison of damping of AISI type 403 stainless
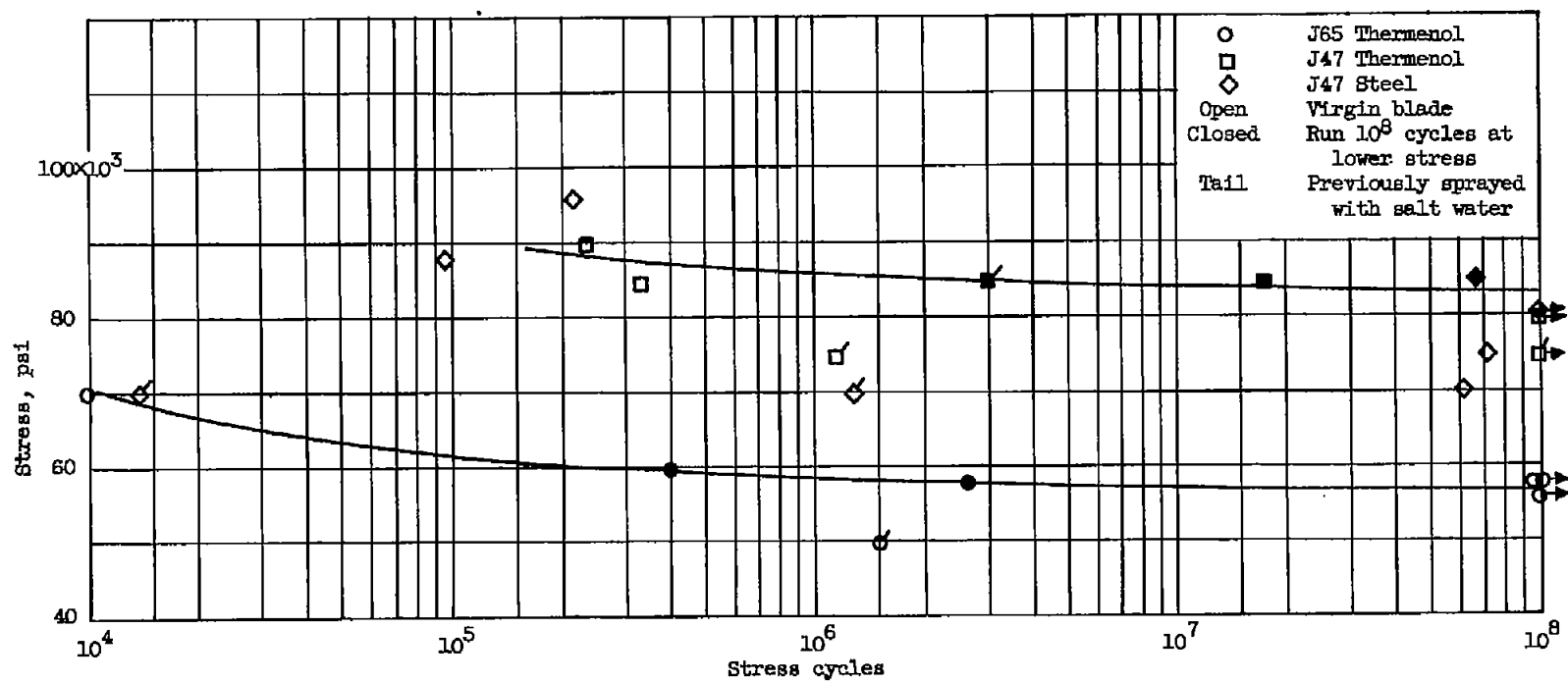steel and thermenol blades.

Figure 6. – Comparison of thermenol and AISI type 403 stainless steel in fatigue.